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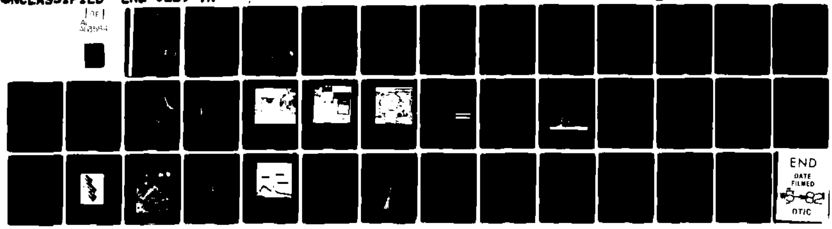

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DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

ELECTRONICS RESEARCH LABORATORY

DEFENCE RESEARCH CENTRE SALISBURY
SOUTH AUSTRALIA

TECHNICAL REPORT

ERL-0229-TR

LASER HYDROGRAPHY IN AUSTRALIA

M.F. PENNY

Approved for Public Release

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LASER HYDROGRAPHY IN AUSTRALIA

M.F. Penny

SUMMARY

In response to a Royal Australian Navy requirement, the Electronics Research Laboratory has developed and evaluated an experimental Laser Airborne Depth Sounder. The system provides discrete soundings, in a rectangular pattern extending 270 m across track, with a nominal spacing between soundings of 10 m. This note describes the experimental system, including the position fixing elements, with emphasis on depth sounding performance.

POSTAL ADDRESS: Chief Superintendent, Electronics Research Laboratory, Box 2151, GPO, Adelaide, South Australia, 5001.

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This paper was presented by Dr D. Wyllie at the Lasers 81 Fourth International Conference on Lasers and Applications, in December 1981, at New Orleans USA.

1. INTRODUCTION

Australia has 2.3 million sq km of continental shelf and a large proportion of these waters is inadequately charted. In some instances charts in current use date back to the days of Matthew Flinders, who explored the coastline 180 years ago. Another feature of the Australian Continental Shelf, shown in figure 1, is the high percentage of hazardous waters it contains, for example the 2 000 km long Great Barrier Reef, which covers an area of 200 000 sq km.

It was against this background, in the early 70s that the Hydrographer of the Royal Australian Navy expressed interest in alternative methods of conducting hydrographic survey. Early reported American work in the field of laser hydrography(ref.1,2) was studied and some feasibility exercises conducted. Fortunately, it was not a cold start for the Electronics Research Laboratory since valuable experience had been gained in the late 60s and early 70s, in developing airborne laser terrain profiling systems for Australian military and civilian land mapping authorities.

Following feasibility exercises, a laser hydrography R & D programme was commenced in 1975. Initially, the programme called for the development of a low repetition rate, non-scanning experimental system designated WRELADS I. This was flight tested in 1977(ref.3,4) and was followed by WRELADS II, a system designed to meet the requirements of the Navy. This experimental system is installed in a Royal Australian Air Force C47 aircraft and has completed a 300 hour programme of test and evaluation trials over North Queensland and South Australian coastal waters.

At the present time an Australian industry consortium has tendered to build two improved versions of WRELADS II, which will be designated LADS (Laser Airborne Depth Sounder). It is intended that LADS be installed in a Fokker F27 and operated by the Royal Australian Navy for hydrographic survey over Australian coastal waters.

2. SYSTEM PHILOSOPHY

The system is designed to operate from an airfield in close proximity to the operating region and, with appropriate ground support equipment, constitute a self contained operation. The survey task however will be shared between the airborne LADS system and surface vessels. In practice LADS will survey all waters within its capability, particularly shallow hazardous waters, with the ship undertaking survey in water where LADS will not perform, viz deep water and more turbid shallow water such as river estuaries etc. The ship or its boats will also assist with placement of transmitting tidal stations.

Limited data processing is undertaken in the air to demonstrate to the system operators that the survey is proceeding satisfactorily however, all prime data are recorded and detailed processing is completed on the ground.

3. SYSTEM DESCRIPTION

Figure 2 shows the operating scenario for WRELADS II, highlighting the laser beam geometry, the position fixing system and the provision of real time tidal information.

A wavelength of 532 nm, as produced by a frequency doubled Nd:YAG laser, has been found well-matched to Australian coastal waters and a suitable laser has been developed in house, exclusively for this task. The system generates a rectangular scanning pattern, 270 m wide with a nominal 10 m spacing between adjacent soundings. Major sections of the WRELADS II system, shown in

figures 3, 4 and 5 and in schematic form in figure 6, will now be briefly described.

Laser

WRELADS II uses a Q-switched frequency doubled Nd:YAG laser generating 5 mJ pulses at a repetition rate of 168 Hz and a pulse width of 5 ns (FWHM). The laser developed for the task is designated FP 3/50 (a 3 mm by 50 mm rod in a short Q-switched Fabry-Perot resonator) and was selected after a detailed study of alternative configurations(ref.5,6 and 7). The prototype laser has successfully completed a 1 000 hour lifetest which included 150 hours operation at an output of 8 mJ. Since April this laser has, without incident, been installed in the C47 aircraft displacing a combination of two 42 pulses/s lasers used as an interim solution.

The laser uses a KD*P Q-switch and a CD*A frequency doubler cut to permit angle tuning over the operating laser temperature range. A high flashlamp simmer current of five amps is used to obtain reliable jitter free operation at 168 Hz. The laser life-test results are shown in figure 7; a flashlamp life in excess of 400 hours has been demonstrated with flashlamp input power increased at regular intervals to maintain constant output.

Beam Geometry

A laser airborne depth sounder obviously uses a laser beam to interrogate the sea bottom with an appropriate across-track scanning system. What is not so obvious is the manner of deriving a reference for the sea depth measurements. One method is to use the surface reflection generated by the scanned beam. However, in conditions of low wind speed and compounded by the presence of swell, the surface reflection can be directed away from the aircraft. In such circumstances, a diffuse backscatter signal from the water may be adequate for reference signal purposes. Such a signal, however, is generated by a volume effect and in clear water, where backscatter is greatly reduced, this technique could introduce errors in depth estimation.

As a consequence, WRELADS II has been designed with a separate IR beam which is vertically stabilized to provide a reliable reference signal (refer figure 8). The IR pulse is a byproduct of the frequency doubling process in the Nd:YAG laser and is therefore coincident with the green output pulse. A drawback of this approach is that when the green beam is not vertical an additional airpath $H(\sec\phi-1)$ must be calculated. This is not difficult since aircraft height (H) is readily obtained from the IR channel, and beam inclination (ϕ) is obtained from a good quality vertical gyro. In this situation a gravity-monitored gyro when tracked along straight flight lines can yield excellent results.

This dual beam method of operation is very reliable over a wide range of environmental conditions. The method also ensures that only a small proportion of wave profile is superimposed on the measured sea bottom profile.

Sounding Pattern

The green beam is reflected from a nodding mirror which is oscillated about two axes to yield a rectangular scanning pattern. Additionally the scanner, and hence the pattern of soundings, is maintained normal to the flight path by correcting for drift angle. This approach uses all laser pulses efficiently, since the spacing between soundings is uniform.

Signal Processing

Following spectral, spatial and polarised filtering the green subsurface

signal is amplified in a photomultiplier detector. This detector an EMI 9813 GB is operated in a high gain, pulsed condition. Over the time period when subsurface signals are expected, the gain is automatically controlled for optimum signal detection. A method of changing the voltage of individual dynodes has been developed in order to modify the gain of the tube. This technique, which compresses dynamic range, permits gain to be changed in a controlled fashion as dictated by backscatter and reflected sunlight throughout the 500 ns time gate of the system, with no significant change in rise time or tube transit time. To allow for high current gain operation, the tube is pulsed on for the required period by a control grid.

The subsurface signal is digitised by a Biomation waveform recorder in real time and stored at two nanosecond intervals, which corresponds to depth increments of approximately 0.2 m. The six bit numbers which comprise the waveform are then clocked out of the waveform recorder at a slower rate and processed to yield depth information in real time. The waveform data are also recorded for post-flight evaluation.

Examples of processed subsurface signals are shown in figure 9, which displays two across-track scans. In all cases the bottom signals are prominent but towards the edge of the scan pattern, when beam inclinations are at a maximum, the surface signal is not present. This is of no concern because the overall timing of the signal is provided by the IR surface reflection.

Postion Fixing

WRELADS uses the Cubic Western Data System ARGO DM54 for position-fixing. This equipment, now in standard use by the hydrographic ships of the RAN, was modified by the company for the high speed airborne WRELADS application. ARGO DM54 operates in the HF band using a shore based chain of transmitting stations. For WRELADS, the system operates in a dedicated hyperbolic format with position fixes established at a rate of three per second. By using a nose to fin antenna, insensitivity to aircraft manoeuvres and a range in daylight of 250 n miles from an inline transmitting chain have been demonstrated.

A small on-board computer, a PDP11-23, is used to convert hyperbolic lane count information to rectilinear Australian Map Grid Coordinates to simplify computation and to aid mission planning and monitoring. The computer also drives a pilot's display for track keeping in straight and level survey runs and for the display of course corrections in the 180° turns at the end of each run. Again all data are recorded for analysis on the ground. The various elements of the navigation/position-fixing systems are shown in figure 10.

Since ambiguity arises in the determination of position by measurement of relative phase, the system must be initialised using known fixed points. In general, this is achieved by fixing the system on the ground before take-off at some previously surveyed point. Although it is common for a pretake-off fix to be held throughout a mission, methods of fixing in the air by day and by night have been developed. Such techniques require the aircraft to be flown over selected fix points, which are viewed and recorded using a bore-sighted, downward-looking video system.

4. PERFORMANCE

Depth performance is dictated by the ability of the system to identify a bottom signal against a noise background. In turbid coastal waters, the dominating noise arises from backscatter as the laser beam propagates through the water column. In clear water, however, reflected sunlight becomes the dominating noise. If this is eliminated by operating at night then

performance is ultimately limited by a shortage of signal photons or system noise.

The relationship between water turbidity in terms of beam attenuation coefficient (c) and extinction depth (d_e), the depth at which the bottom signal becomes lost in noise for the WRELADS system is shown in figure 11. This empirical relationship, established for the system operating at 500 m above the sea, applies to day time conditions.

The data presented in figure 11 were obtained on a 1 200 km mission from Townsville to the Torres Strait(ref.8). A zig zag track was followed through the reef waters (see figure 12) which provided many opportunities for the determination of extinction depth. Figure 13 shows the beam attenuation coefficient estimated from backscatter observations made on the same flight. These latter data have most significant implications since if turbidity can be estimated reliably then extinction depths can be predicted. Thus, with a knowledge of extinction depth d_e, and if no bottom is detected, it can be assumed that the water is deeper than d_e. With appropriate safety margins this approach will make possible the class of sounding "No bottom at ...". The actual range of (c) determined in this sortie covered two orders of magnitude ie 0.05 m^{-1} at Ribbon Reef and 5.0 m^{-1} in the Torres Strait. It is of some interest to note that the same region of the Torres Strait was line profiled in June 1977 with WRELADS I, in that instance, excellent bottom signals were recorded. The difference between the two results can be attributed to 35 to 45 kn winds and the rough seas existing at the time of the recent trial. Such conditions would be expected to produce vertical mixing and hence, because of the shallow bottom, an increase in water turbidity. In deeper water this effect is not pronounced as verified by the measured depth of 50 m off Ribbon Reef.

A survey of a selected reef has been completed and a photograph of a model, constructed using WRELADS data, is shown in figure 14. This survey, which took approximately one minute of flying time, covered one square kilometre. In figure 15 a section of the reef facing the lagoon is shown. The coral heads were detected by the depth sounder with excellent relative correlation with the ground truth contained in the photograph.

As a user, the Hydrographer needs statistics which permit coastal zones of interest to be characterised in terms of water turbidity and depth combinations that are within the sounding capability of the system. Figure 16 shows all beam attenuation coefficients recorded in the Gulf St Vincent, South Australia. The curve shows the depth sounding performance objective for LADS. With other data, this indicates that in excess of 50% or 200 000 sq km of the South Australian Gulf waters should lie within the capability of the LADS system.

Turbidity

In North Queensland coastal waters extreme values of turbidity are encountered. Thus, in order to promote system capability, factors which introduce change of turbidity must be studied. It has been observed that sustained wind and the seas which develop tend to increase turbidity in shallow water but have little effect in deep water. Other likely causes are coastal rivers which, in the wet season, discharge huge volumes of particulate matter into the sea.

Studies of water turbidity and the related statistics of the Australian Continental Shelf, which are essential for the efficient deployment of LADS,

are reported in references 9 and 10. At the Electronics Research Laboratory, emphasis has been placed on beam attenuation measurements since the technique involved is precise, repeatable and readily related to the measurement of other relevant parameters such as diffuse attenuation coefficient. Transmissometers have been developed to measure beam attenuation coefficient as a function of wavelength and a considerable amount of data gathered. As an example, at the present time, the hydrographic vessel HMAS Moresby, on an opportunity basis, is gathering data in coastal waters between Perth and Darwin.

The next phase, the estimation of beam attenuation coefficient from airborne observations of laser backscatter, is now proving a most useful technique. Although it offers speed in data gathering, it is still a very slow method of collecting statistical data. The long term method will be the use of satellite pictures in combination with limited ground truth information. In order to meet the Australian requirement, a mixture of the three methods will be used.

Anomalies

Various anomalies have been briefly studied in the WRELADS programme. They range from foreign bodies in the sea which reflect the laser beam to bird strikes which cause false reference signals. Figure 17 shows one example of a submerged foreign body encountered off Cairns in North Queensland. The bottom depth was consistently 43 m in this area as denoted by the right hand pulse. The intermediate pulse, which appeared on several soundings, indicated the presence of a reflecting body 20 m long and 3 m off the bottom.

Another anomaly studied in North Queensland was submerged plankton and other living organisms which scatter laser radiation. Figure 18 shows a sequence of subsurface signals where this type of anomaly was encountered. The bulge in the backscatter envelope is attributed to some form of marine life, and its presence at the depth 12 to 18 m was verified by transmissometer readings obtained from a surface vessel. This type of anomaly occurs infrequently and, in some 50 hours of flying in reef waters, the case illustrated was the most severe encountered. Since bulges in the backscatter envelopes can be eliminated by appropriate filtering, anomalies of this type should not be recognised as bottom reflections.

In summary, anomalies which do not present a high frequency edge in the subsurface signal (eg the case described above) can be discriminated against by signal processing. Large rays, whales or dense fish concentrations however, will reflect the laser beam and produce signals which may be falsely identified as the bottom. In these circumstances it may be impossible to resolve such an ambiguity without reflying the mission.

Depth Accuracy

Depth is calculated from a carefully measured time interval and a knowledge of the velocity of light in water. It is assumed that the laser energy is refracted at a flat sea surface (along the path AB in figure 19) and reflected back to the receiver along the reciprocal path (BA). In practice, due to waves, ripples, multiple scattering in the water and a relatively large receiver field of view, the average path length of signal photons is increased (eg path ADE in figure 19). This effect exaggerates depth and is a major contribution to bias error. Provided that methods of calibrating the system can be devised, then such errors can be greatly reduced.

Random errors contributed by the system and the environment remain as the major problem. If receiver bandwidth, digitising interval and timing standards are adequate then the major error contribution arises from the need

to process pulses with a wide signal to noise ratio, a wide dynamic range and poor risetimes, the latter being inherent in the beam broadening phenomenon mentioned in the previous paragraph. Solutions to these problems involve the use of various techniques to limit dynamic range and constant fraction discriminators to minimise timing errors.

Environmental factors which effect accuracy are depth, sea state (which influences the refraction process), turbidity (which controls the multiple scatter process) and errors caused by sea bottom vegetation (which prematurely reflects the laser radiation).

Although operation over fresh water would justify a change of propagation constant, over the sea (with salinity changes of a few parts per thousand and a 20°C temperature band) the use of a fixed propagation constant yields negligible errors. Errors due to tide prediction must also be considered since hydrographers are concerned with referencing data to a low water datum.

The study of system depth errors has not been completed. However, results have been obtained from several aircraft/ship exercises conducted in November 1980 over selected flat bottom areas in water 20 and 30 m deep and referred to a convenient tidal datum. These exercises yielded the following information.

Depth	Bias Error	Random Error (SD)
20 m	0.76 m	0.45 m
30 m	0.87 m	0.55 m

System shortcomings in the calculation of the term $H(\sec\phi-1)$, evident at the time of these trials, have since been overcome and a reduction in the random error is expected. Trials currently in progress should verify this.

Tidal Corrections

WRELADS measures water depth referenced to mean sea level existing at the time of the measurement, but such soundings must be referred to a low water datum. It is proposed that LADS use telemetered tide gauges which transmit to the aircraft. With this real time input and the use of co-tidal charts (charts relating sea height and time in a given area), tidal corrections can be established over the survey area.

Calibration

The hydrographic community require data generated with a high confidence level. Traditionally, echo sounders are calibrated against a bar suspended below the vessel and attached by two calibrated wires. This is the ultimate calibration of the system and is performed at regular intervals.

Despite exhaustive facilities for internally checking the calibration of LADS, a need for a simple realistic calibration is evident, ie, an equivalent of the suspended bar. If the transmitting tide gauge can be mounted in a location where the bottom is level, then the telemetered true depth can be monitored in the aircraft and compared with the measured value. Although the tide gauge can be located by the aircraft by using the position fixing system, it is most desirable to identify the tide buoy using the downward-looking video. Protection against movement or destruction of such tide gauges either

deliberately by vandals or inadvertently by fishing trawlers is necessary.

Accuracy - Horizontal

Errors in the horizontal coordinates of a particular depth sounding have two major contributions: errors in the determination of aircraft position and errors in the prediction of sounding position relative to the aircraft. The latter is largely determined by errors in pitch, roll and azimuth angles. As an example, errors of one degree in pitch and roll will each shift the predicted sounding by 9 m, but the same error in azimuth will cause an error of 2.5 m and will only be apparent at the extreme edges of the sounding pattern. It is estimated that the total error arising from angular uncertainty will be held to 5 m.

Determination of position of sounding from the aircraft, based on angles and aircraft height, locates the point on the sea surface irradiated by the laser. The location of the sounding on the bottom can also be predicted based on depth and a refraction process assuming a flat sea. Small perturbations in sounding position due to swell are negligible.

Errors which arise with HF phaselocked systems, as used by surface vessels, are reported in reference 11. The fundamental difference with WRELADS is the introduction of height as a variable, which it was thought would modify the propagation non-uniformity observed at sea level. These non-uniformities are routinely handled on surface vessels by introducing an offset factor known as the locking constant. The data shown plotted in figure 20 were recorded on a trial where, at three separate altitudes, ten passes were made over a target, the Orontes Bank Light, with boresighted downward-looking video to determine aircraft relative position. This work has not been completed, but the inference at this stage, based on limited analysis, is that the non-uniformities in propagation at sea level are not significantly different at the WRELADS operational altitude of 500 m with the equipment working in passive hyperbolic mode.

In summary, horizontal positional accuracy, on the base line, with a calibrated system is estimated at 10 m where 7 m represents ARGO errors and 5 m represents the aircraft to sea pointing errors. The latter error occurs twice, once in the ARGO calibration process which may be undertaken in the air, and again in the determination of sounding position.

Navigation

Navigation for hydrographic survey can be divided into three functions: ferry legs, straight line survey runs and 180° turns between runs. Navigation programmes have been developed for these functions and utilise a small CRT for a pilot's display. This display is computer controlled and indicates track error by lateral displacement of a small diamond and height error by its vertical displacement. Some indicative runs have been monitored using the C47 with manual pilot control as indicated in the table.

Since the sounding pattern width is 268 m, a survey planned to advance in 200 m increments will require track error to be held to 20 m RMS. This appears to be attainable. Precision 180° turns are required with alignment over the start point with errors of less than 20 m.

Navy operation of LADS will provide for autopilot control of the straight survey legs and pilot control with a computer controlled display for the 180° turns.

TRACK LENGTH (km)	TRACK ERROR	
	RMS (m)	MAX (m)
8.6	50.1	102.8*
30.0	9.5	33.9
30.0	9.0	27.6
30.0	23.2	69.3
92.7	23.4	84.0
128.7	13.4	55.8

* New pilot

5. SAFETY

The system has been designed to be eye safe at sea level for day and night operations, meeting Australian Standard 2211-1981.

6. CONCLUDING REMARKS

Laser airborne hydrography can be used to provide a significant contribution in the survey of Australian coastal waters. The airborne system will provide high density data and share with surface vessels the total survey task. In shallow, clear or moderately clear water and especially in hazardous waters, the airborne operation will dominate, but in turbid and deep water, the surface ship, with its acoustic sounder, will remain unchallenged.

The technology is still very new and brings with it significant changes for hydrographers. In data processing for example, conventional hydrographic survey is undertaken with a degree of human monitoring. With laser hydrography, producing two million soundings per five-hour mission, only minimal human intervention and monitoring of data are possible.

The WRELADS R & D Programme has permitted investigation of most facets of the total task. This R & D requirement has biased the design of the experimental equipment and, in consequence, LADS, the production version, is to be built expressly for operational use in a F27 aircraft.

7. ACKNOWLEDGEMENTS

The work reported in this paper was undertaken at the Electronics Research Laboratory with assistance from the Advanced Engineering Laboratory and the RAAF Aircraft Research and Development Unit. Also acknowledged is the support received from the RAN Hydrographic Service and my colleagues Dave Phillips, Don Rees, Ralph Abbot and Doug Faulkner, who contributed to this paper.

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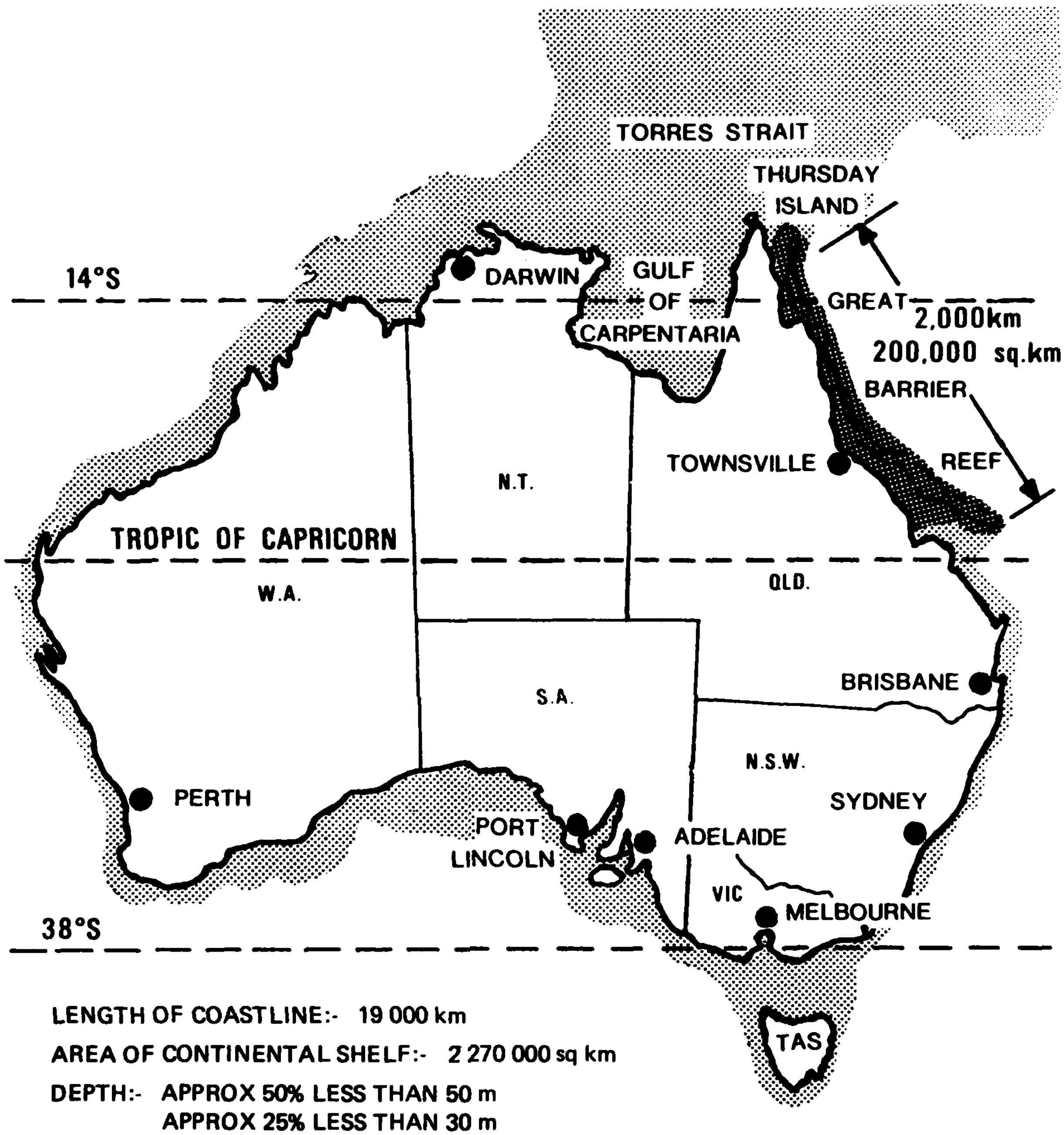

Figure 1. The Australian continental shelf

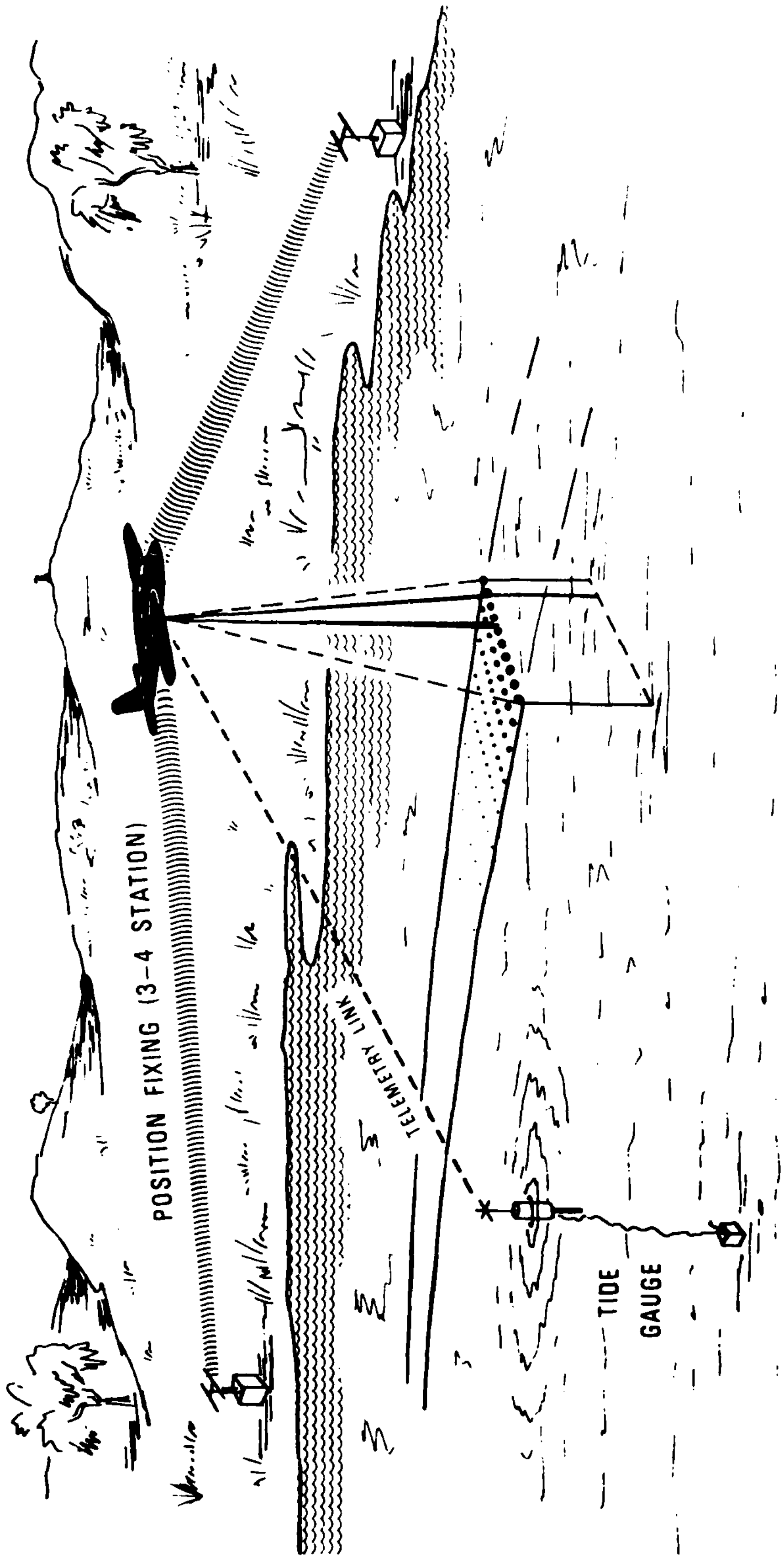

Figure 2. WRELADS operating scenario

Figure 3. WRELADS II installed in C47

Figure 4. C47 installation showing position fixing and navigation rack

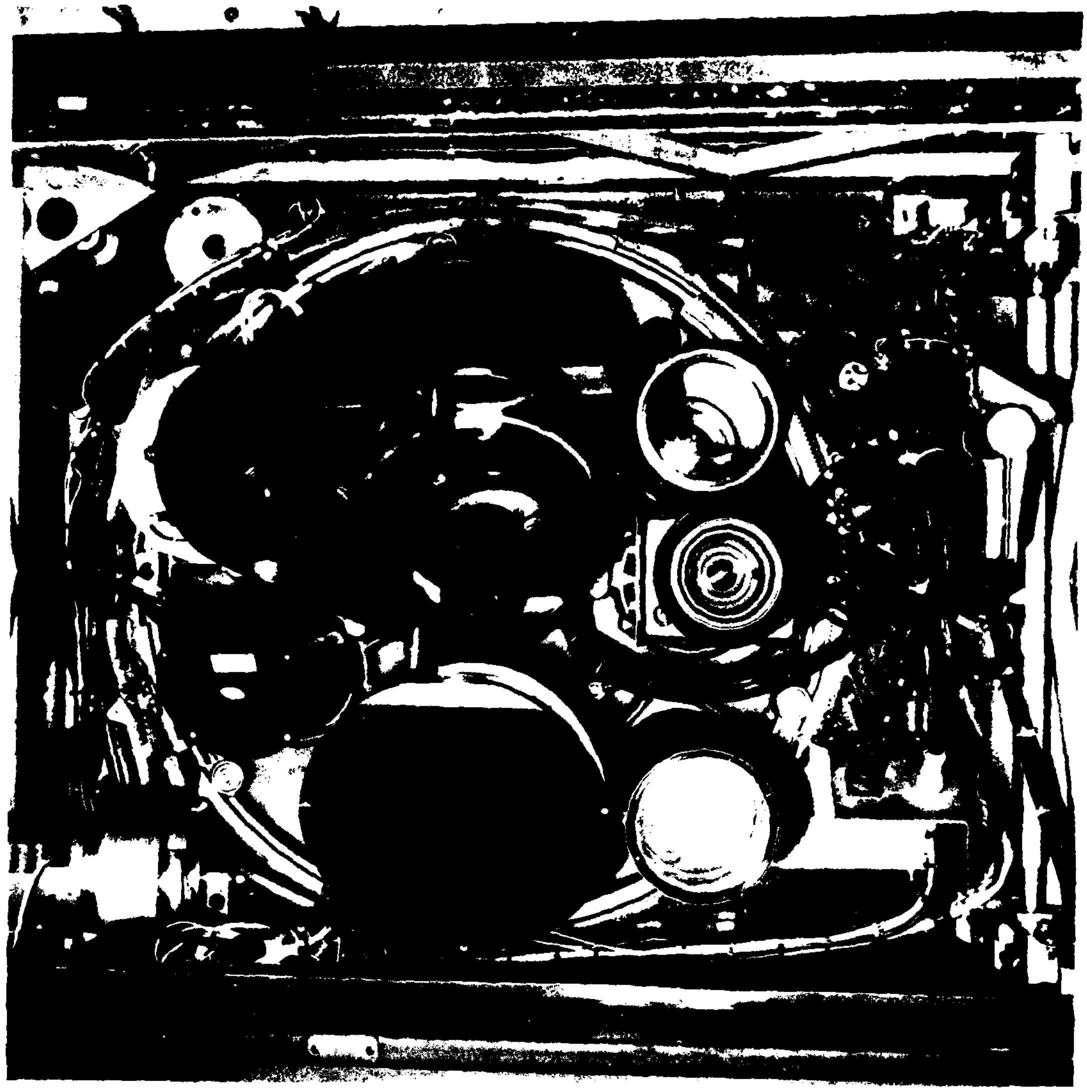

Figure 5. WRELADS under floor optical bay

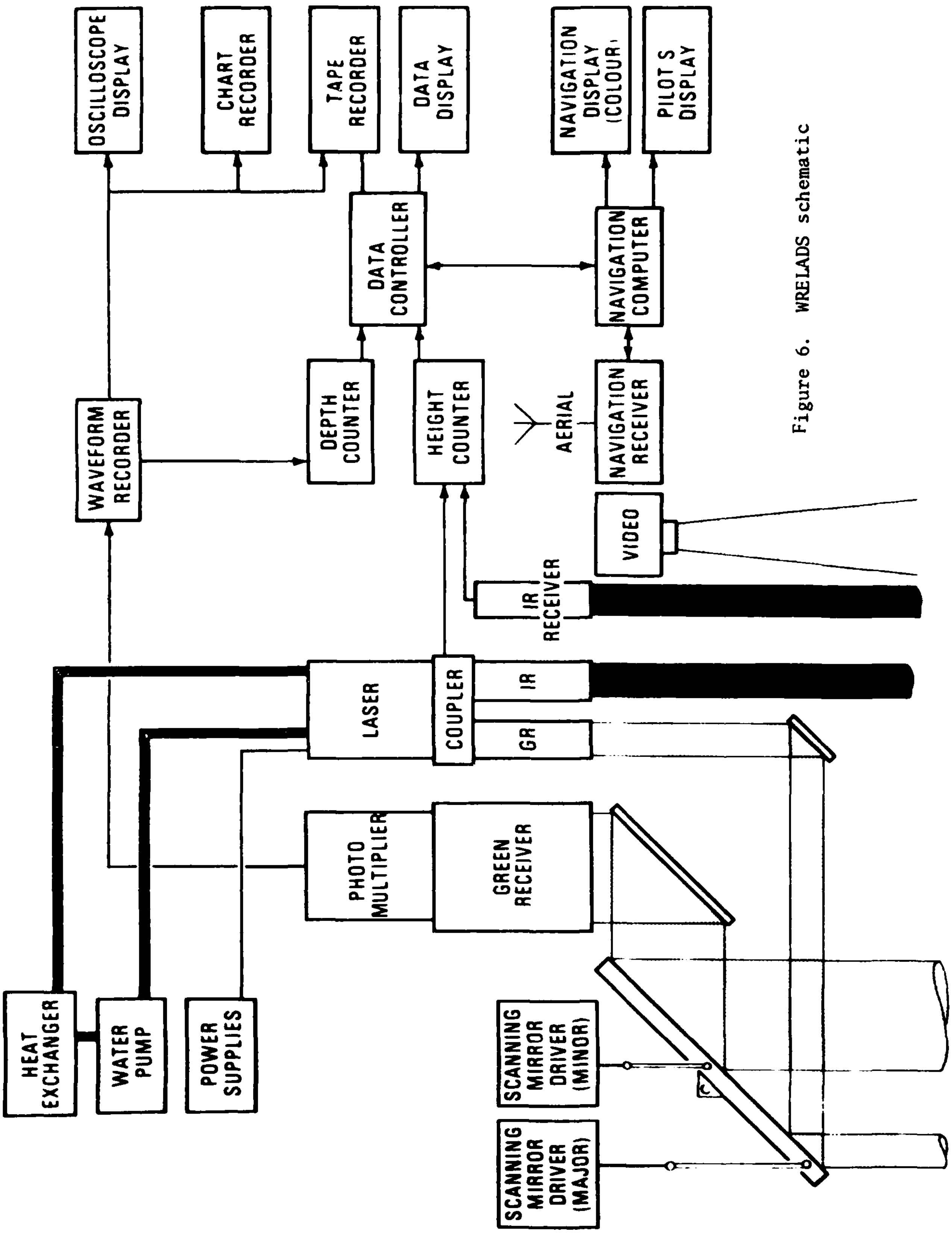

Figure 6. WRELADS schematic

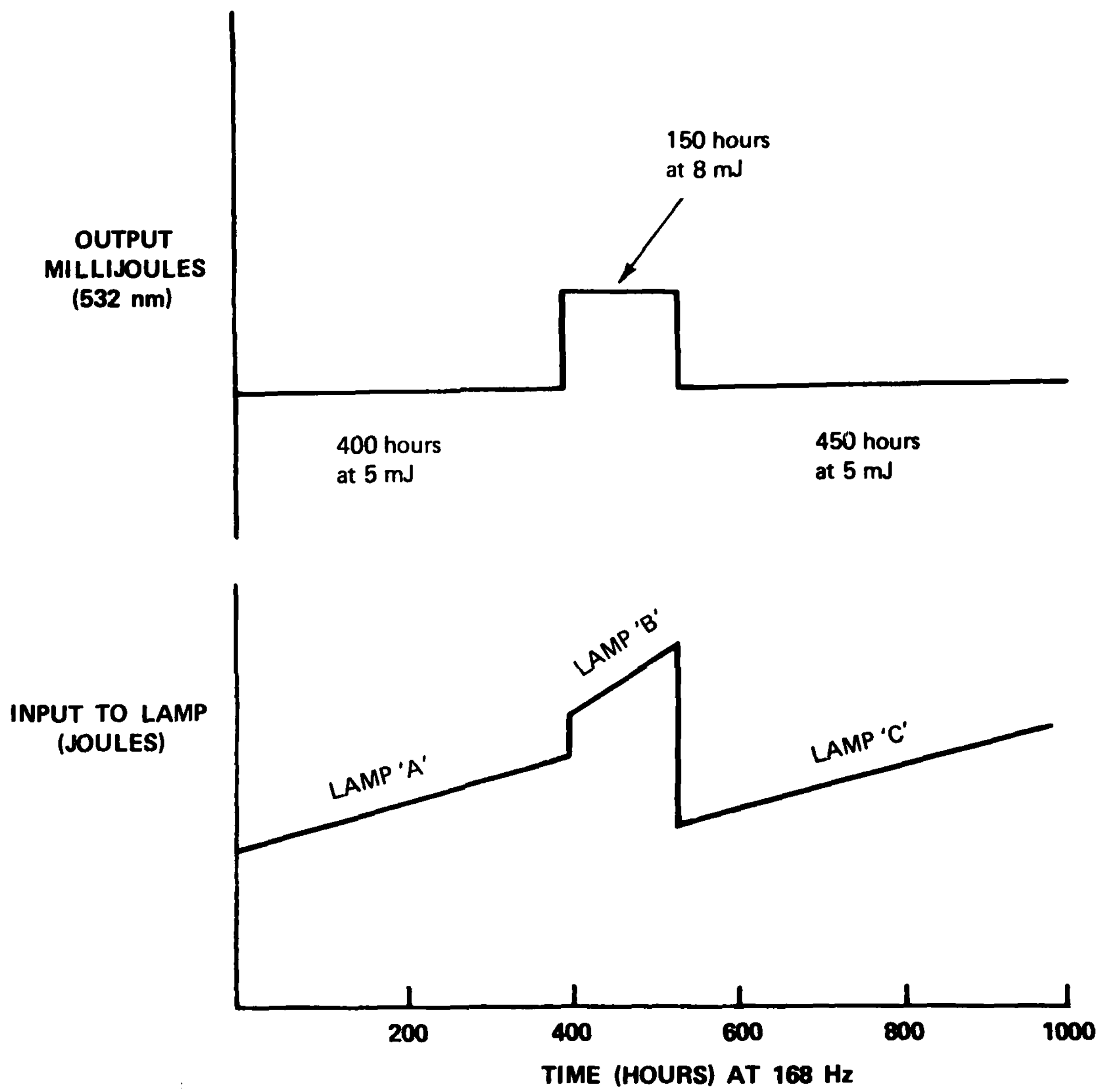

Figure 7. Laser FP3/50 1000 hour life-text

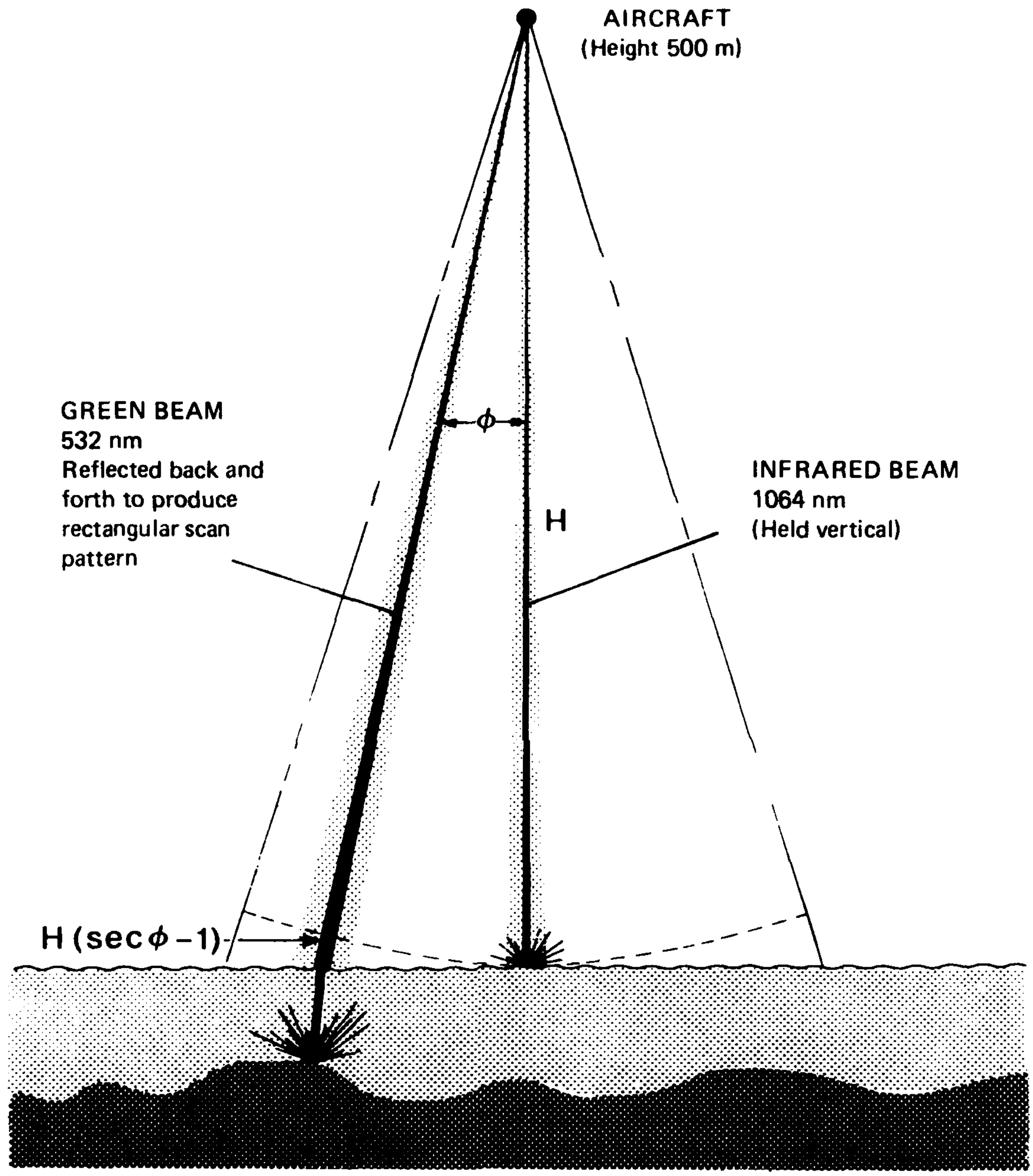

Figure 8. Beam scanning geometry

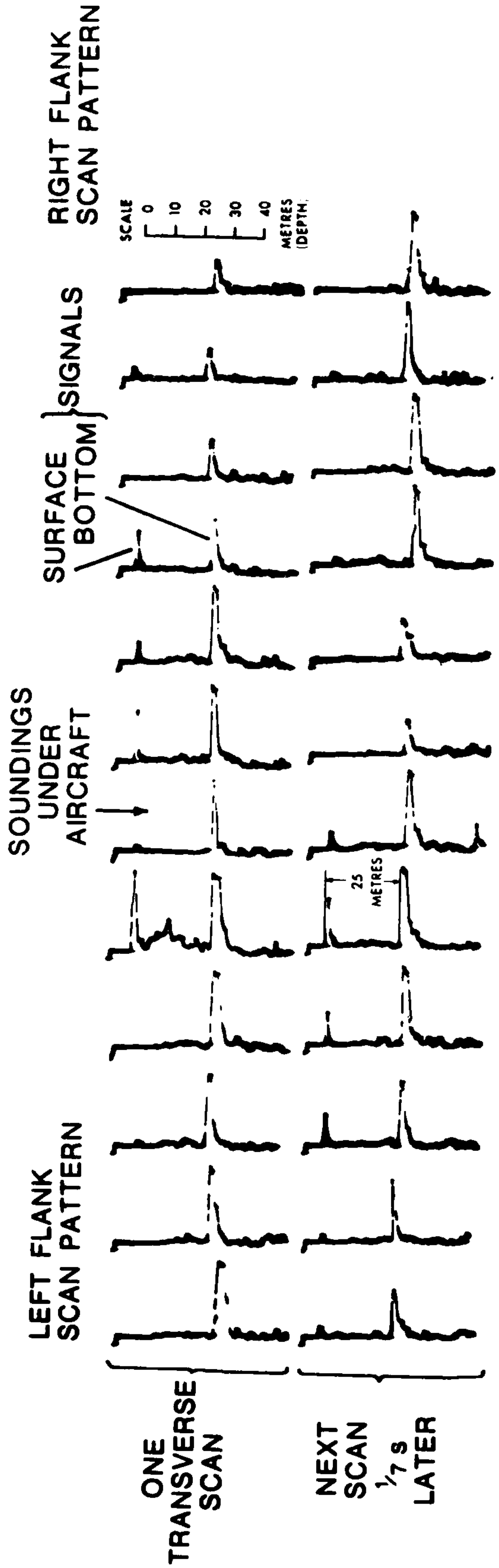

Figure 9. Subsurface signals

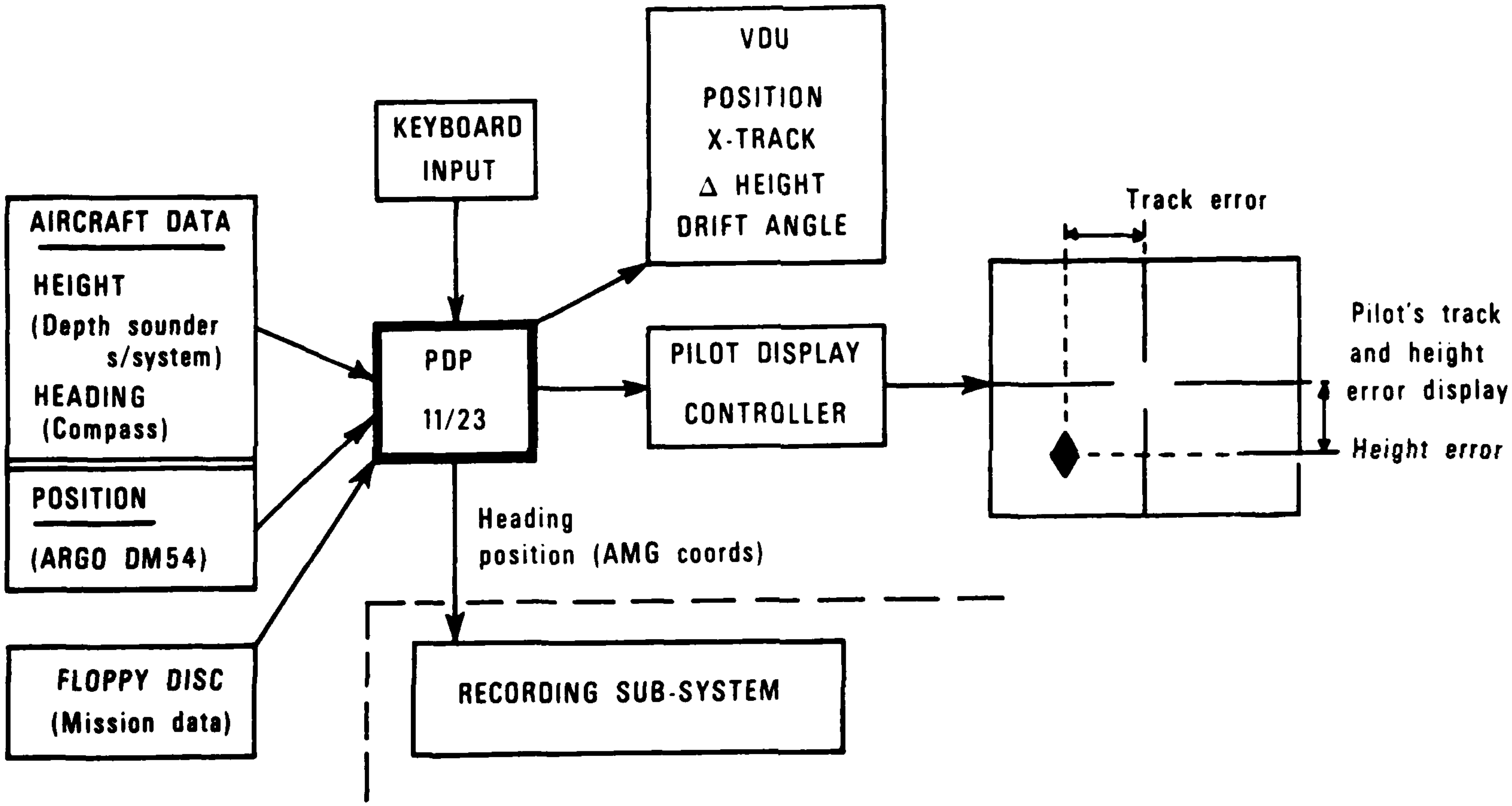

Figure 10. WRELADS II. Aircraft navigation sub-system

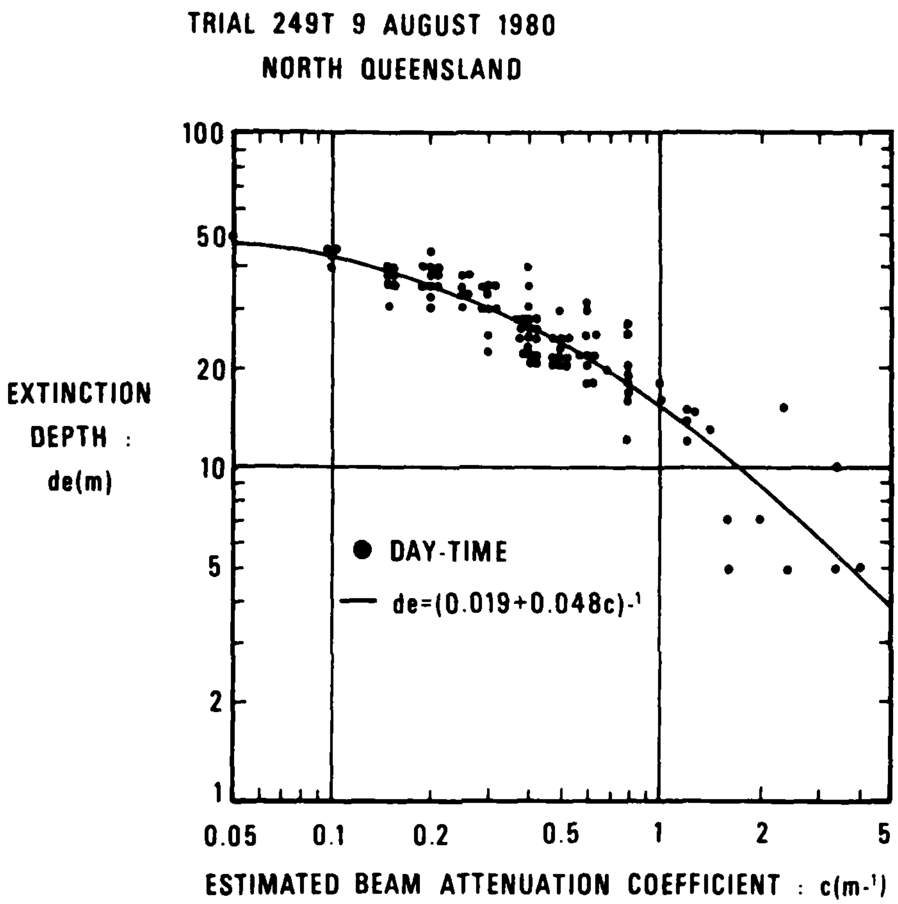

Figure 11. Dependence of extinction depth on water turbidity

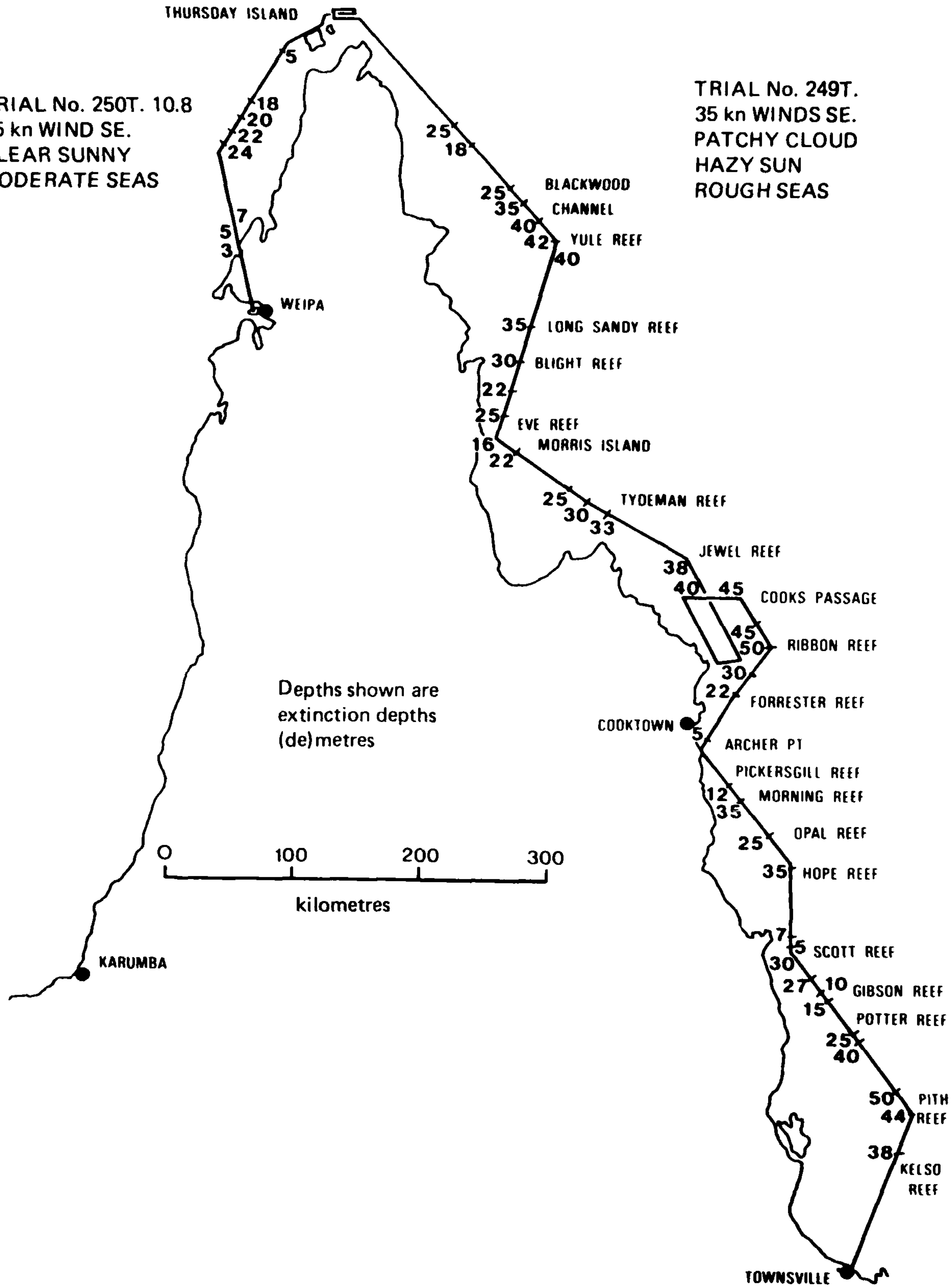

Figure 12. Extinction depths in north Queensland coastal waters

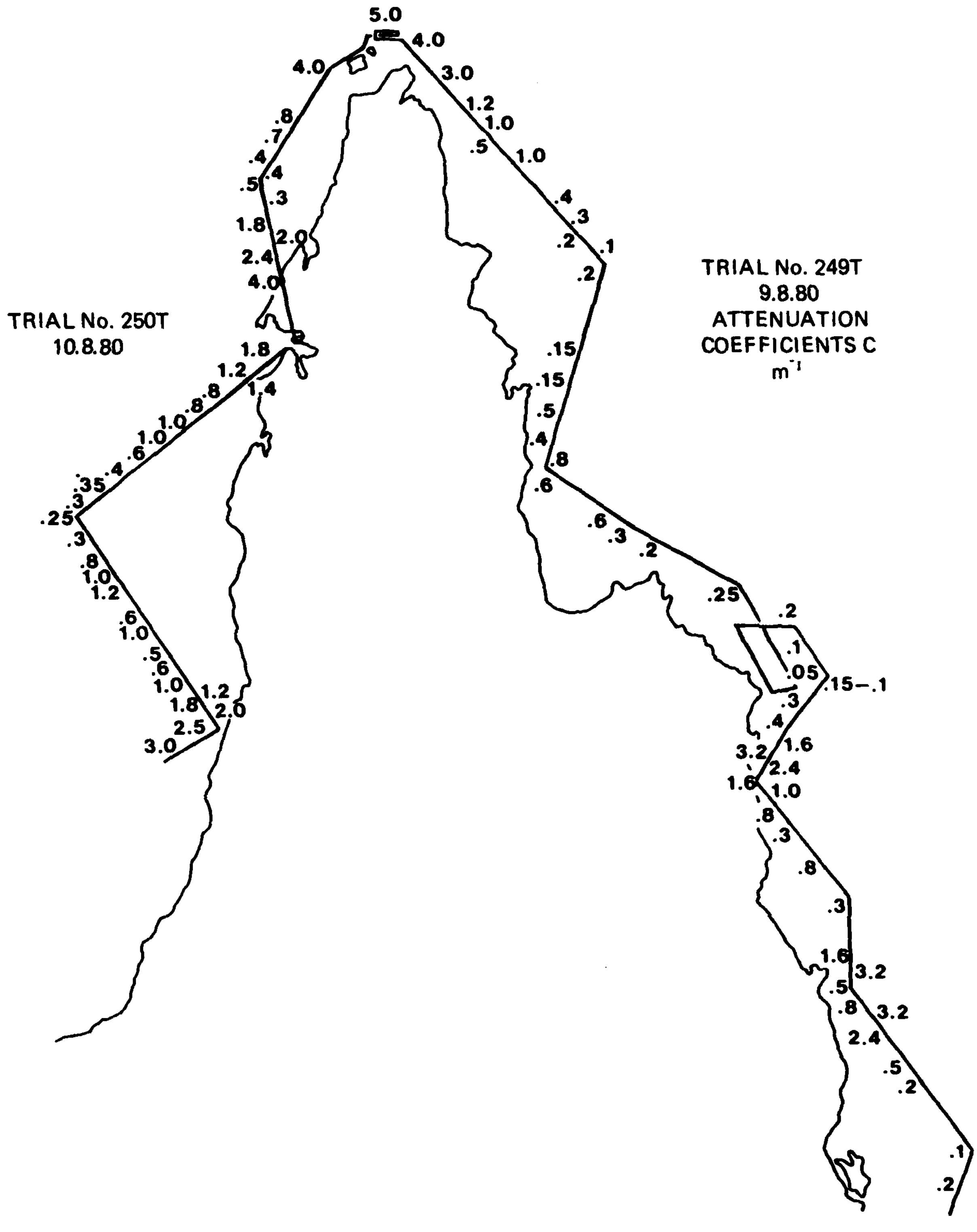

Figure 13. Estimated turbidity - north Queensland coastal waters

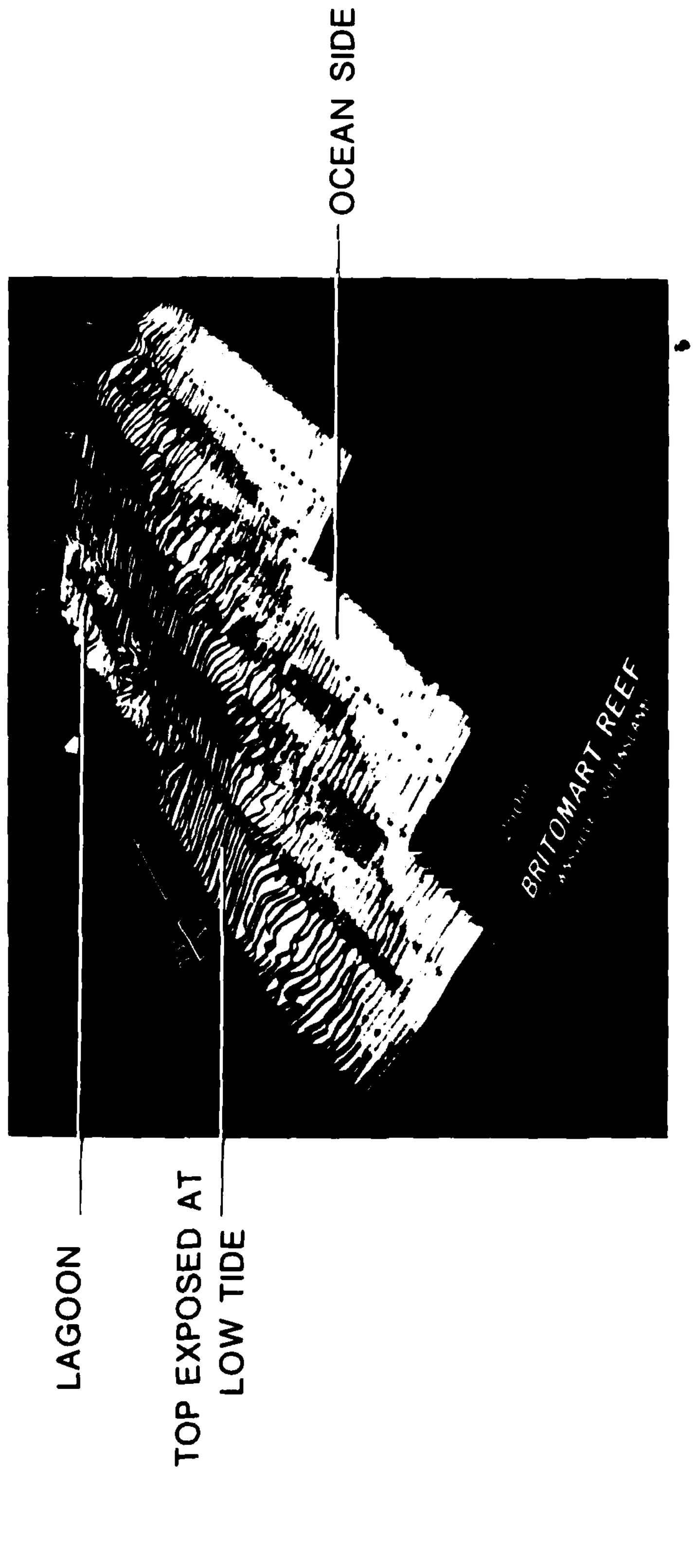

Figure 14. Britomart Reef model

Figure 15. Reef micro survey

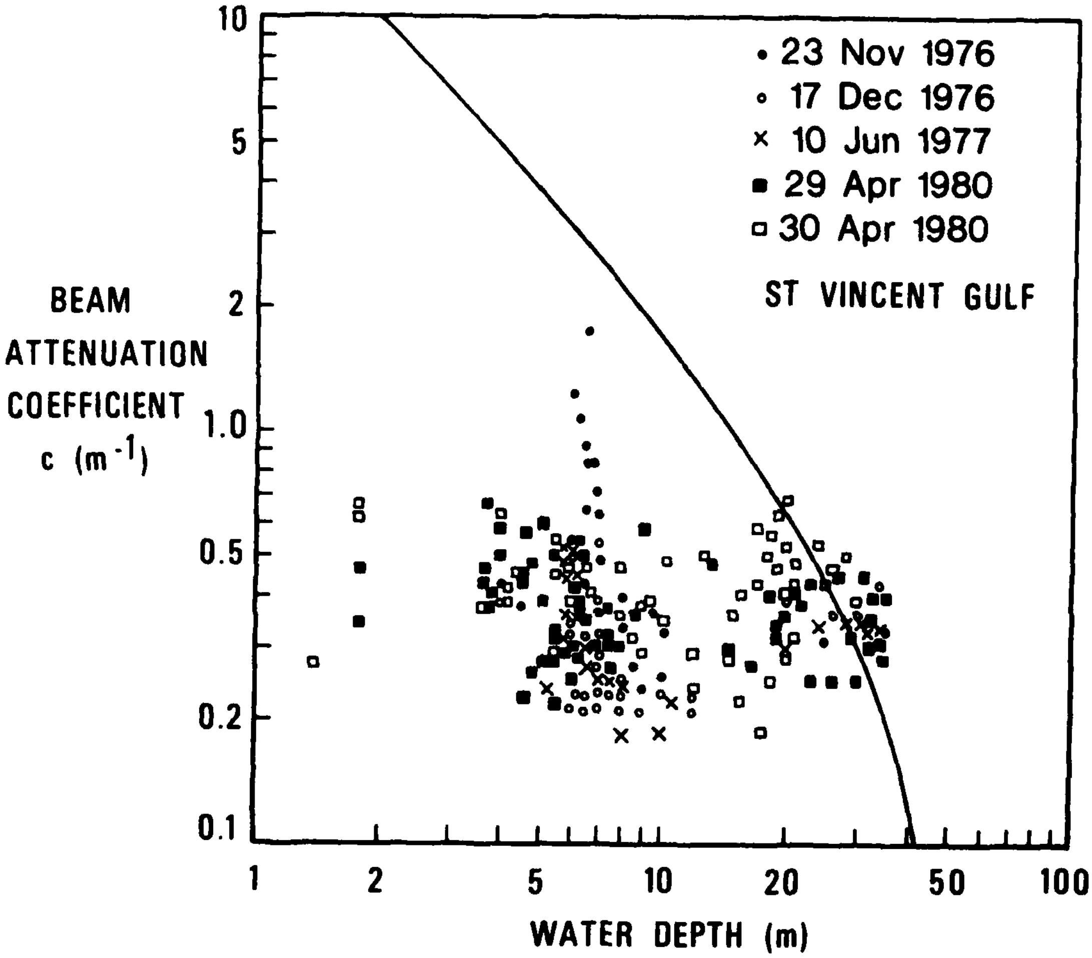

Figure 16. Gulf St Vincent: Scatter diagram beam attenuation coefficients versus depth

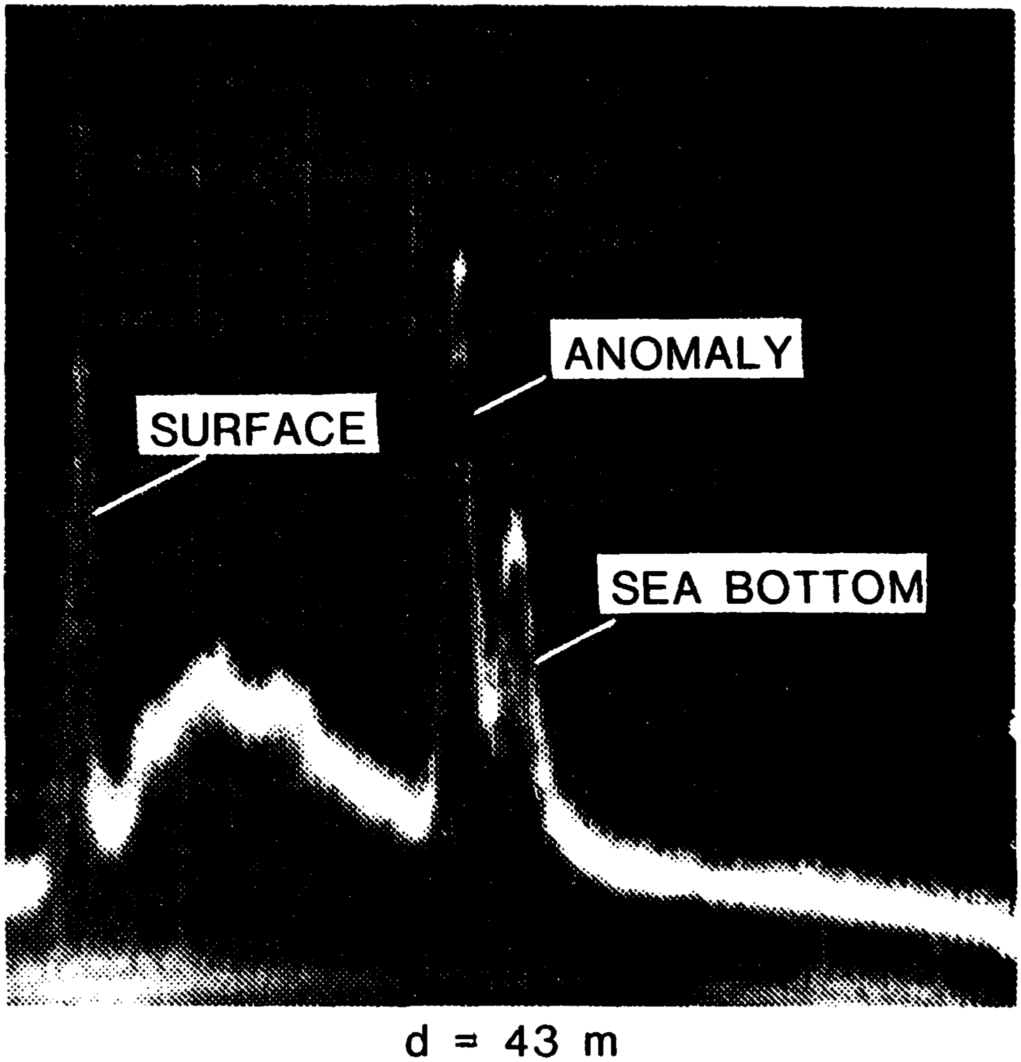

Figure 17. Anomaly encountered off Cairns

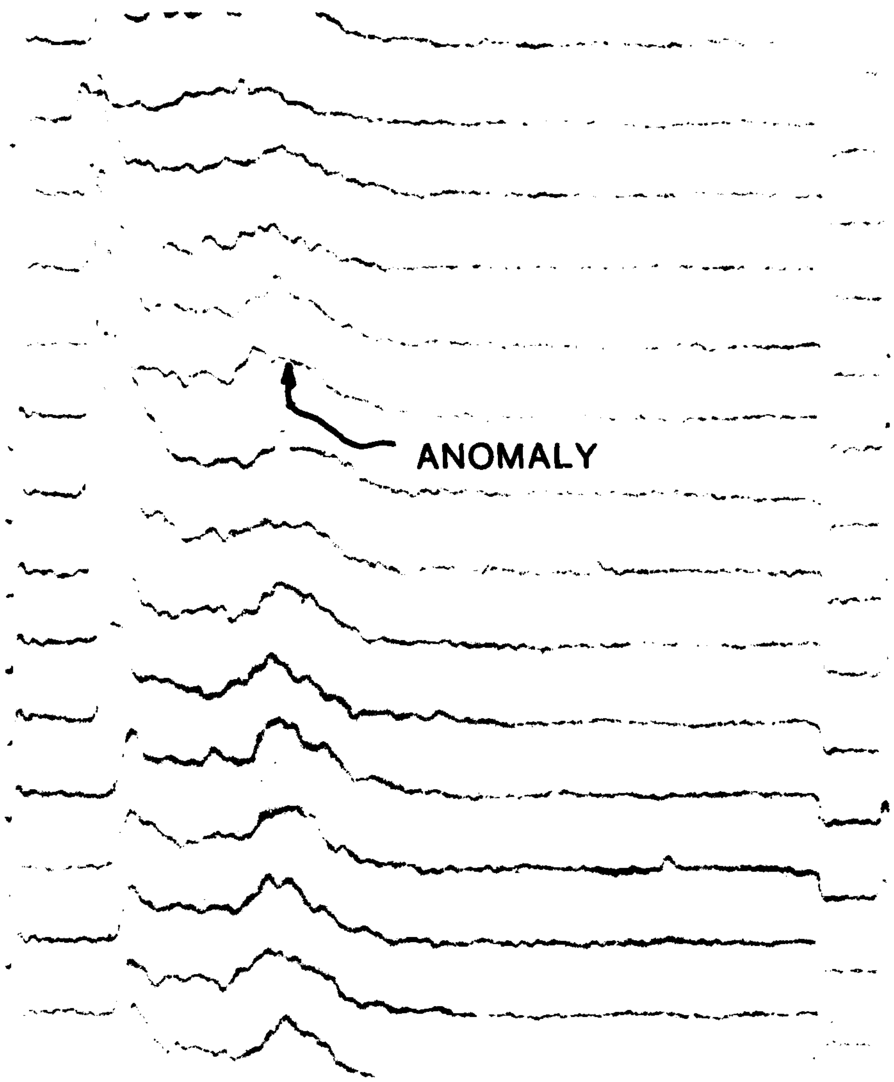

Figure 18. Backscatter anomaly encountered off Hinchinbrook Island

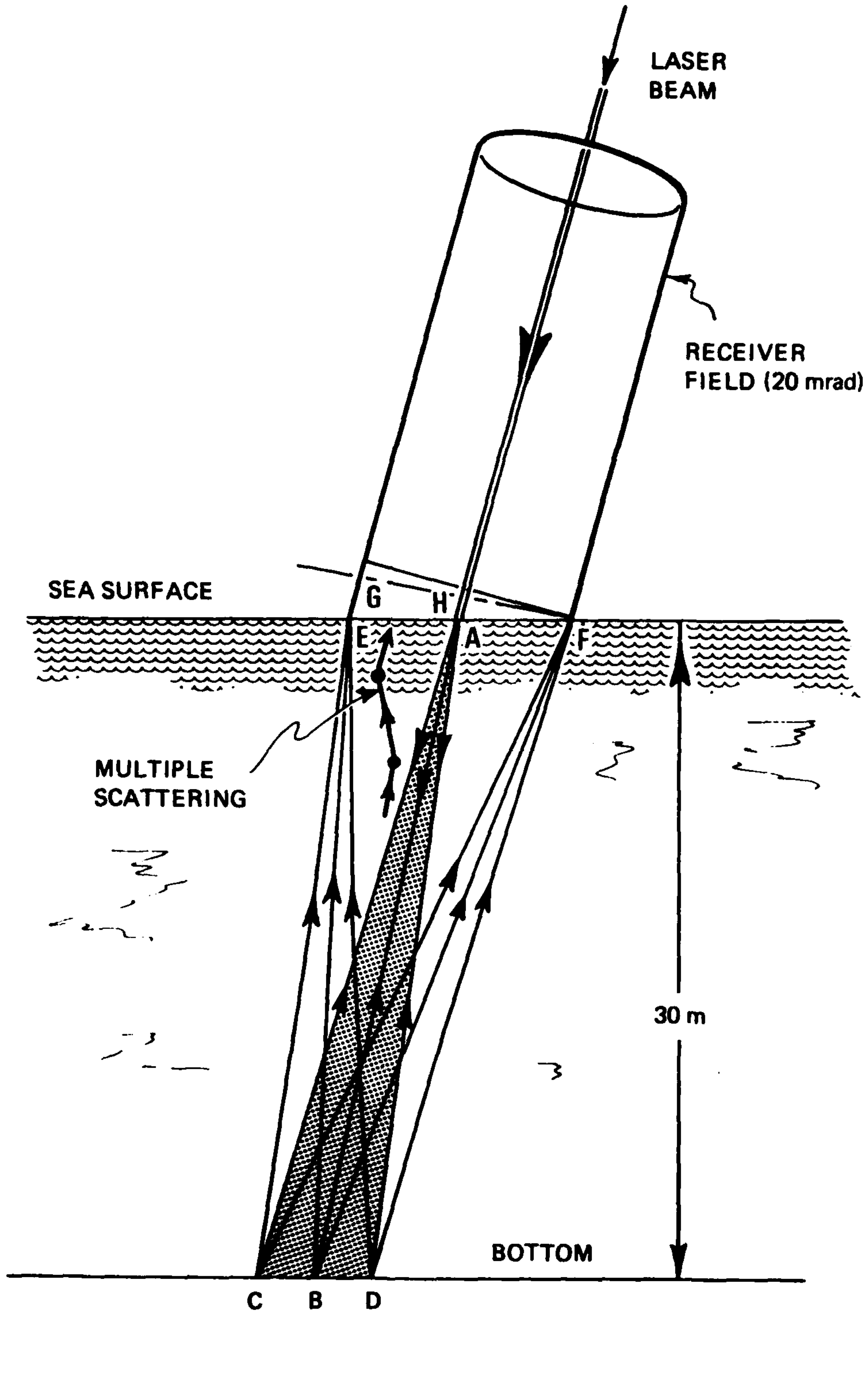

Figure 19. Subsurface ray paths

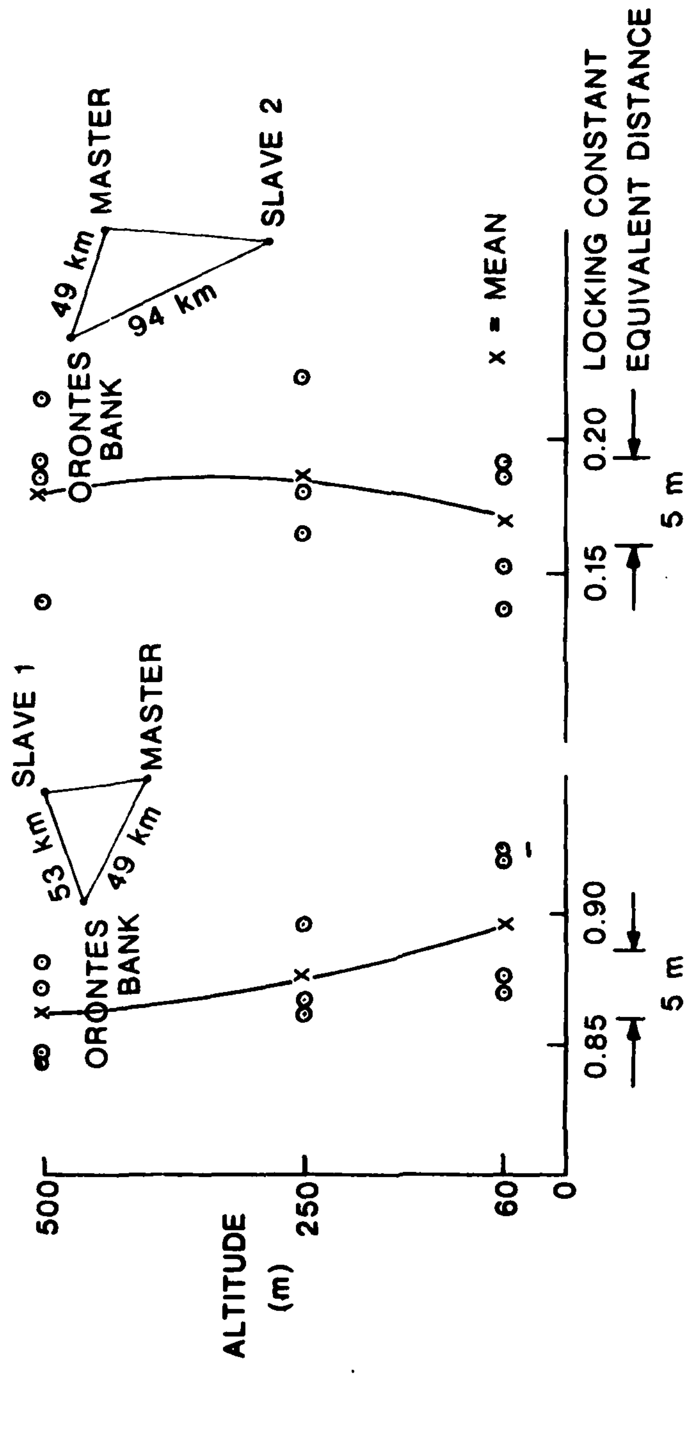

Figure 20. Locking constant as a function of altitude

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16 SUMMARY OR ABSTRACT:
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In response to a Royal Australian Navy requirement, the Electronics Research Laboratory has developed and evaluated an experimental Laser Airborne Depth Sounder. The system provides discrete soundings, in a rectangular pattern extending 270 m across track, with a nominal spacing between soundings of 10 m. This note describes the experimental system, including the position fixing elements, with emphasis on depth sounding performance.

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